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Key Points:

- Spatiotemporal patterns of the annual and seasonal means of ground surface temperature are similar to those of surface air temperature
- There is a dramatic increase of differences between ground temperature and air temperature in northern China in winter since 2005
- The contrasted tendency of GST and SAT seems due to the increase of snow depth in northern China (north of 40°N) in winter in recent decade

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Spatiotemporal variations of differences between surface air and ground temperatures in China

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Abstract This study analyzed the temporal evolution and spatial distribution of the difference between ground surface temperature (GST) and surface air temperature (SAT) in China based on monthly station data (1970–2015). Overall, the spatial patterns and temporal evolutions of the annual and seasonal means of GST are similar to those of SAT. However, a dramatic increase in the difference between GST and SAT in northern China in winter is observed since 2005, which is due to a pronounced increase of GST and a slight decrease of SAT. The interdecadal variations of the tendencies of GST and SAT appear associated with the increase of snow depth in northern China (north of 40°N) in winter in recent decades, especially in northern Xinjiang, northern Inner Mongolia, and most parts of Northeast China. The connection of snow depth with the variation of GST-SAT obtained from the station observations was consistent with that based on reanalysis data.

1. Introduction

Land-atmosphere interactions play an important role in shaping regional climate and its variability and in determining its predictability [*National Research Council*, 2010]. Ground surface temperature (GST), as a key land surface parameter, through interaction with atmosphere, has considerable influences on climate variations [*Liu and Avissar*, 1999; *Wang et al.*, 2013]. For example, by comparing the surface air temperature (SAT) and GST, *Beltrami et al.* [2005] noted that GST was consistent with SAT. *Qian et al.* [2011] suggested that the warming trend of soil temperature in Canada was associated with an increase of SAT. *Wu and Zhang* [2014] investigated the role of ground temperature-atmosphere coupling in influencing interannual variability of summer climate over East Asia by analyzing regional climate model simulations and argued that subsurface soil temperature feedbacks played an important role in amplifying summer SAT variability over arid and semi-arid regions of eastern Asia. *Mahanama et al.* [2008] analyzed the influences of subsurface soil temperature on interannual variability of SAT using long-term simulations of atmospheric general circulation models. They suggested that subsurface soil temperature significantly can increase SAT variability and memory in most regions.

In fact, the interactions between land (ground temperature) and atmosphere are very complex and variable in both space and time. They are largely affected by changes within the lower atmosphere and of ground features, e.g., changes of SAT, GST, vegetation, soil moisture, and other variables. Previous works have documented the complex relationship between GST and SAT [*Beltrami et al.*, 2003, 2006; *Woodbury et al.*, 2009; *Roy and Chapman*, 2012]. For example, *Zhang et al.* [2001] argued that increasing snow depth in early winter (October–November) and early melting of snow in spring might be the main reasons for the increase of soil temperature in Irkutsk and Russia via the effects of insulation and albedo changes. The annual mean SAT can be 1–11°C lower than the annual mean soil temperature at high latitude because of the insulating effects of snow in winter and surface organic layer in summer [*Smith*, 1975; *Smith and Riseborough*, 2002]. *Zhang et al.* [2005] noted that the long-term changes in soil temperature can be different from that of SAT because changes in land surface variations (i.e., vegetation, snow, and soil moisture) and climate variables (i.e., precipitation, solar radiation, and humidity) can all impact the exchanges of water and energy fluxes between the atmosphere and the soil and further modulate the relationship between SAT and soil temperature. Therefore, we cannot simply treat the measured warming trend in SAT as soil temperature.

Furthermore, it has been well recognized that in addition to forcing from ocean, land-atmosphere interaction is another factor playing an important role in affecting climate predictability [*National Research Council*, 2010]. For example, *Hu and Feng* [2004a, 2004b] indicated that soil temperature can “remember” climate anomalies and release their effects in subsequent seasons. The memory of soil temperature can be considered as a potential predictor for seasonal climate anomalies and extremes [*Yang and Zhang*, 2016]. *National Research Council* [2010] pointed out that realistic initialization of land surface feature (such as soil moisture and snow cover) and realistic description of land-atmosphere coupling in a model may increase accuracy of precipitation and temperature predictions. Thus, studying the impact of land on atmosphere may have potential to improve seasonal-interannual climate prediction.

China has different types of climate and various vegetation and soil conditions; the interaction between ground surface temperature and atmosphere might be also complex, which had substantial effects on climate variations and predictability [*Wang et al*., 2013; *Wu and Zhang*, 2014]. Nevertheless, there have been few studies on these issues because of the lack of adequate GST data. Recently, a long-term quality controlled GST data set for China has been developed from historical records by the National Meteorological Information Center (NIMIC) of China Meteorological Administration, which has made such a study possible.

The objective of this research is to investigate the temporal evolution and spatial patterns of the differences between GST and SAT in China based on 46 year records of GST and SAT data and examine the possible impact of change in winter snow depth on the interdecadal variation of the difference between GST and SAT. The results of this study have the potential to provide information for further assessing the impacts and feedbacks of land on atmosphere and might also supply some evidences to understand climate variations in China with aim to improve short-term climate forecast. The remainder of the paper is organized as follows. Section 2 provides a brief description of the data used in this analysis. The results and discussion are reported in section 3, and a summary is presented in section 4.

2. Data and Methods

2.1. Data Sources

Data were provided by the NIMIC of China Meteorological Administration, including monthly mean GST, SAT, and snow depth for more than 2000 national reference climatic and basic meteorological stations across China from 1960 to 2015. The GST was taken as the 0 cm temperature of the land surface, which was measured by placing a surface geothermometer on the bare ground with the body and bulb of the geothermometer half buried within the soil. The monthly mean GST does have some missing values, especially during the 1960s, so 1899 stations with at least 40 years' historical data obtained during 1970–2015 were selected from the data set. Figure 1 shows the spatial distribution of GST stations and the geographical divisions of China. In addition, monthly mean SAT and snow depth at each of the 1899 stations (Figure 1) during 1970–2015 were used. The snow depth is taken as the vertical depth from snow surface layer to snowy ground surface, which is measured once a day if it snowed, and the daily value of snow depth is obtained by calculating the means of snow depth at a station and its surrounding.

To verify the connection between snow depth and the variation of the difference between GST and SAT, obtained from the station data, the National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) reanalysis (R1) data (1970–2015) were used [*Kalnay et al*., 1996]. The analyzed variables included monthly mean water equivalent of accumulated snow depth (kg/m^2), 2 m (T2m) air temperature, and 0–10 cm (T0-10cm) underground temperature. Here the water equivalent of accumulated snow depth is referred to as snow depth, and T2m and T0-10cm are used to represent SAT and GST, respectively.

2.2. Data Processing

Monthly means of GST, AST, and snow depth are all the averages from corresponding daily mean data of more than 2000 meteorological stations from 1961 to 2015. All these daily data have been quality controlled by the NIMIC [*Ren and Xiong*, 2007], and the procedure is as follows: first, the climate extreme values of data are checked by seeing if they exceed a certain standard deviation, such as 3 standard deviations. If the absolute value is larger than 3 standard deviations, it then sets up as missing value. Second, time continuities of data are detected. If an abrupt shift in mean values caused by station relocation is found, the time series are adjusted through shifting the earlier part of the time series by the difference in the mean values before and after the relocation [*Wang and Gaffen*, 2001]. Third, spatial consistencies of data are checked by spatial regression test. Spatial regression tests employ the data from neighboring stations to make reference datum at the

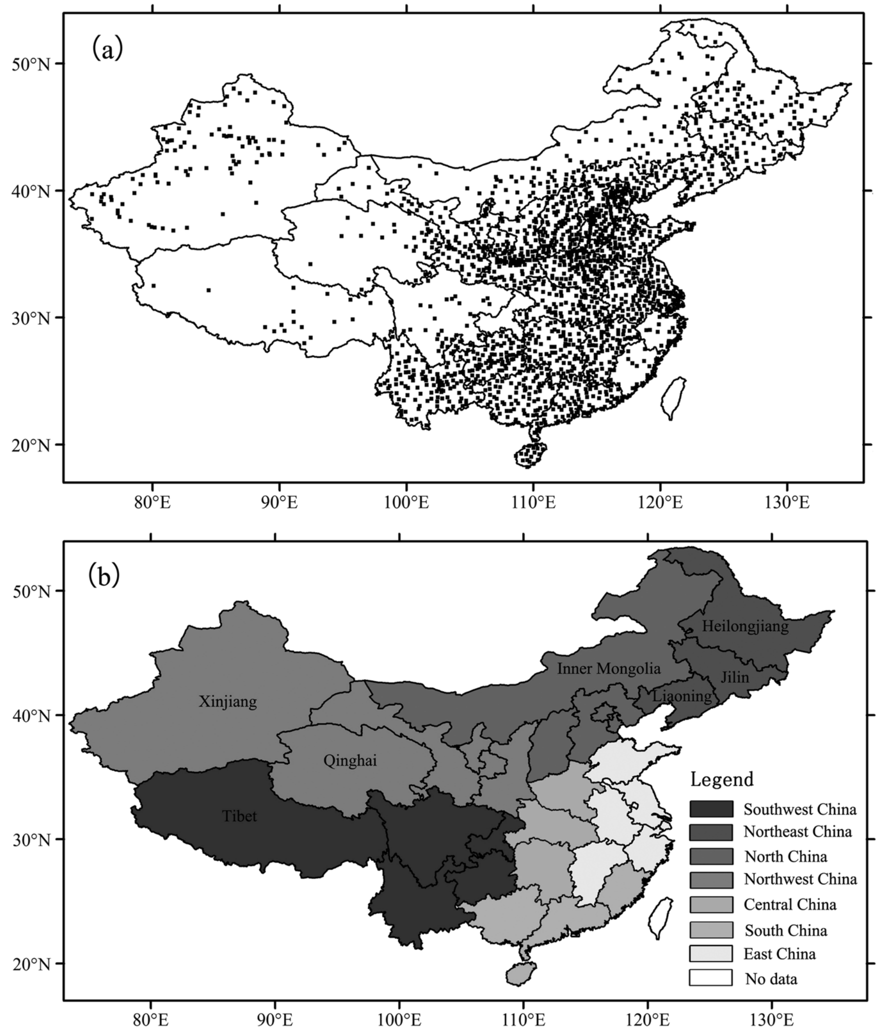

Figure 1. (a) Spatial distribution of GST and SAT stations and (b) the geographical divisions across mainland China.

station of interest by linear regression equation. If the difference between observation and reference datum of the station felled within the confidence interval formed from neighboring station data during a time period of length according to the regression equation, then the observation is considered spatial consistency, otherwise, be treated as erroneous datum [*You et al.*, 2008]. After above data processing, the quality and consistency of the data are guaranteed.

Monthly means of GST, AST, and snow depth are all the average from corresponding daily data. The processing procedure is as follows: when the days with valid daily values are equal or greater than 23 days in a given month, all the valid data would be averaged as the monthly mean data; if the days with valid values are less than 23 days or the data were missing in any 1 month of a given season, then the whole month or season would be treated as missing values.

3. Results and Discussion

3.1. Spatial Distributions of Difference Between GST and SAT

Figure 2 shows the spatial distributions of annual and seasonal mean differences between GST and SAT (GST-SAT). It can be seen that both the amplitude and the pattern of the differences vary with season and geographic location. Overall, the differences of GST-SAT are largest in summer (June-July-August, JJA) and smallest in autumn (September-October-November, SON). In summer, the differences are positive and within the range of 1.4 to 10.1°C. Spatially, the differences decrease gradually from northern and western China to

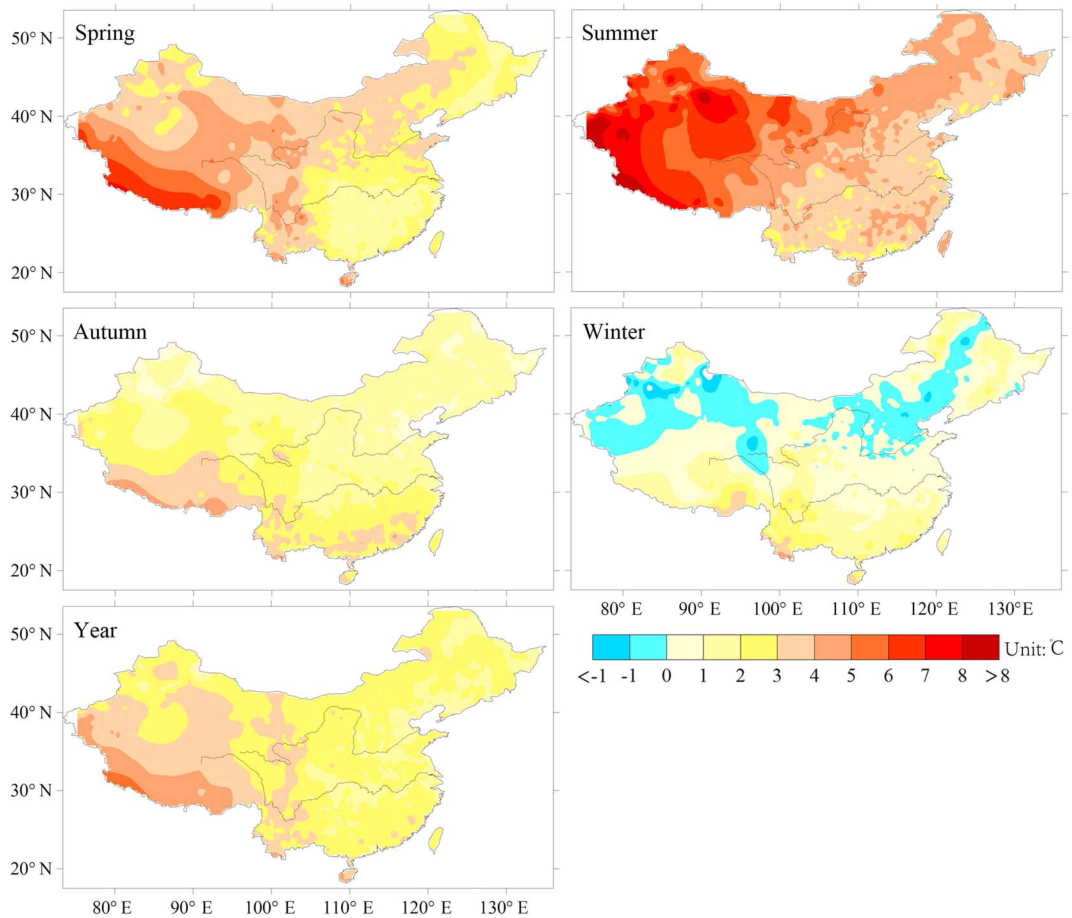

Figure 2. Annual and seasonal mean of GST-SAT in China averaged over 1970–2015.

southern and eastern China. In spring (March-April-May, MAM), the averaged differences of GST-SAT are positive and within the range of 0.5 to 7.2°C, i.e., lower than summer. The spatial distribution of the differences of GST-SAT is similar to summer, with higher values in northern and western China and lower values in southern and eastern China.

In autumn, the averaged differences of GST-SAT range from 0.1 to 5.0°C, with higher values across most parts of the Tibetan Plateau and parts of South China. The spatial contrast in winter and autumn is much smaller than that in summer and spring. Whereas the differences of GST-SAT are positive in summer, spring, and autumn (i.e., GSTs > SATs), the differences become negative in some areas in winter (December-January-February, DJF), suggesting that GST is lower than SAT (Figure 2). We speculate that these negative differences might be partially attributable to snow variation, which is discussed in section 3.3.

For the annual mean, the differences between GST and SAT range from 0.6 to 5.8°C. The largest values are across the Tibetan Plateau and parts of the Yungui Plateau, while the smallest values in the high latitudes might be attributable to the cancellation effect of the negative values in winter and the positive values in the other three seasons. The annual and seasonal mean values are high across the Tibetan Plateau, especially in western and southern parts. However, it should be noted that the detailed distribution of the high values might be unreliable because there are few stations in this region and the effects of spatial interpolation could be significant.

3.2. Temporal Variations of Difference Between GST and SAT

Figure 3 shows the temporal variations of annual and seasonal mean GST and SAT, and the GST-SAT difference averaged for all the stations in China. Pronounced warming trends are evident for both GST and SAT in all seasonal and annual mean traces, suggesting overall warming trends in China [*Hu et al.*, 2003]. For

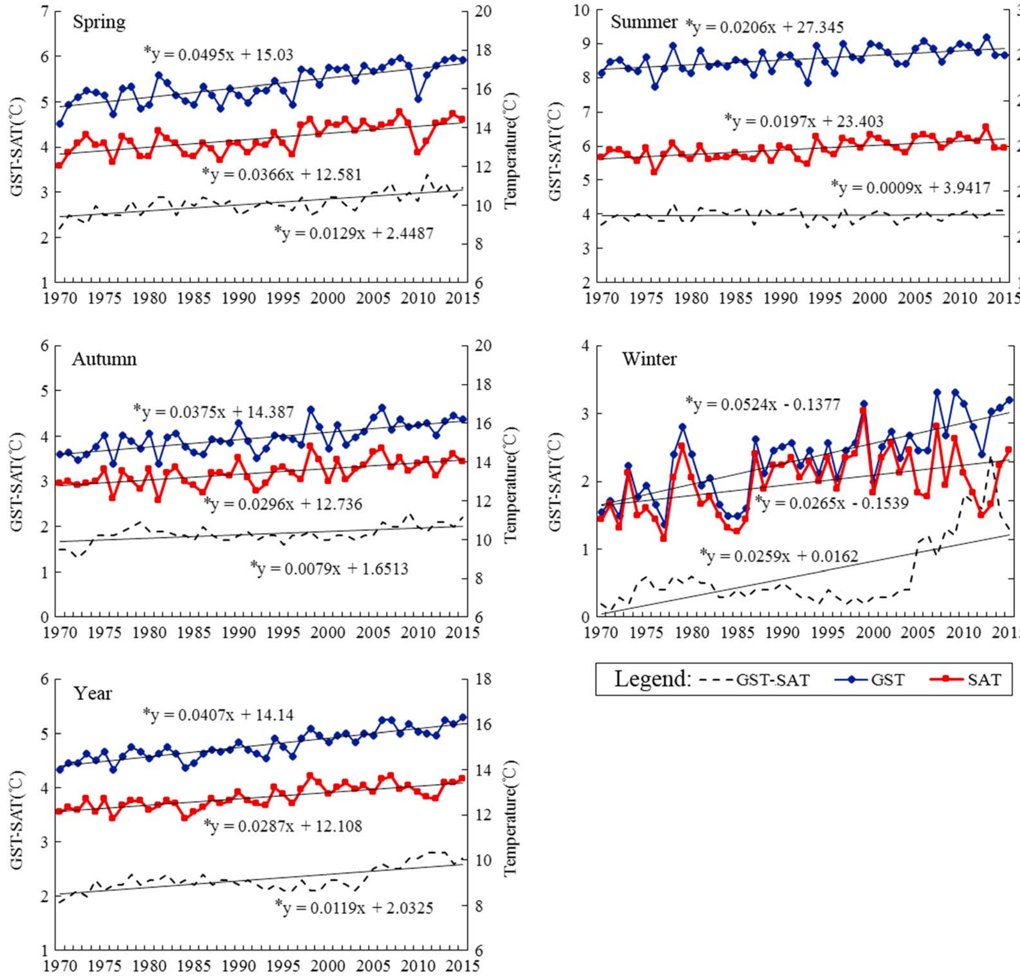

Figure 3. Temporal variations of seasonal and annual means of GST, SAT, and GST-SAT averaged in China over 1970–2015, together with their linear fitting. The asterisks denote the significance of trends at the 0.05 confidence level by the Mann-Kendall test.

the 1970–2015 averages, the GSTs are larger than SATs both annually and seasonally; the difference is largest in summer (3.9°C) and smallest in winter (0.6°C; Table 1). In addition to the similarity of the linear trends, the interannual variations of the annual and the seasonal averages of GST are similar to SAT, implying close connection between GST and SAT.

Interestingly, the differences between GST and SAT in winter, spring, and autumn all display evident increasing trends, although these trends are much smaller than found for GST and SAT separately (Table 1). It is noteworthy that there is a sharp increase in the difference between GST and SAT in winter

Table 1. Comparisons of the Main Characteristics of GST and SAT in China

	GST		SAT			
	Means (°C)	Trends (°C/Decade)	Means (°C)	Trends (°C/Decade)	GST-SAT (°C)	Trends (°C/Decade)
Annual	15.1	0.41*	12.8	0.29*	2.3	0.12*
DJF	1.1	0.50*	0.5	0.30*	0.6	0.26*
MAM	16.2	0.49*	13.4	0.37*	2.8	0.13*
JJA	27.8	0.21*	23.9	0.20*	3.9	0.01
SON	15.2	0.38*	13.4	0.30*	1.8	0.08*

*Significance of trends at the 0.05 confidence level by the Mann-Kendall test.

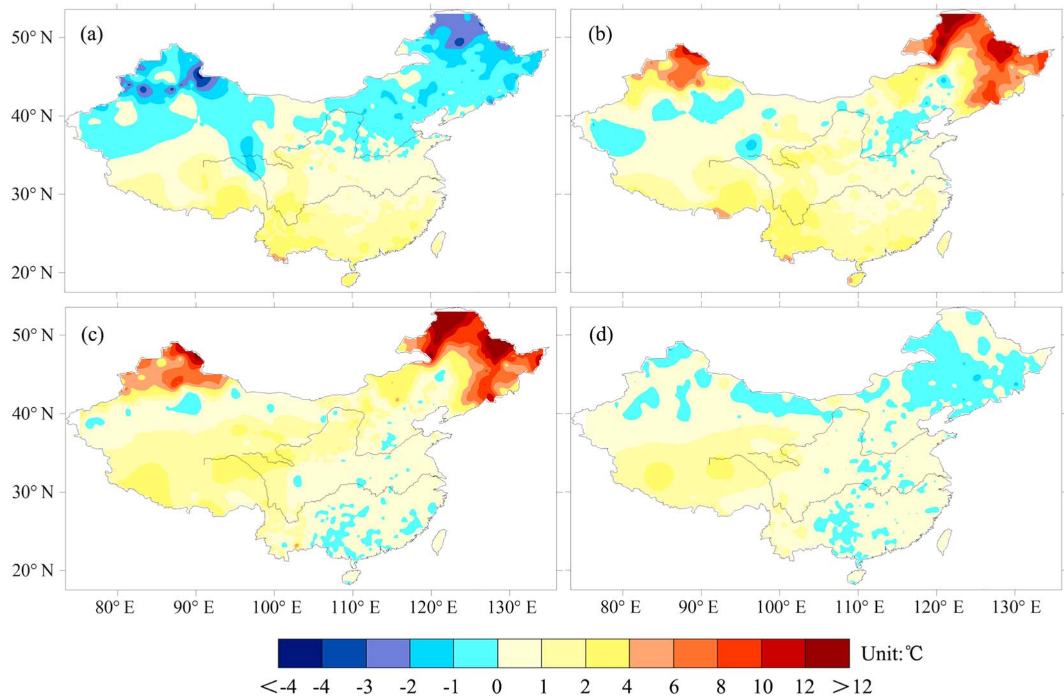

Figure 4. (a) Mean difference of GST-SAT over 1970–2004; (b) mean difference of GST-SAT over 2005–2015; (c) mean difference of GST between 2005–2015 and 1970–2004; (d) mean difference of SAT between 2005–2015 and 1970–2004.

from 2004 to 2005. To investigate this dramatic change, the spatial distributions of GST-SAT averaged for 1970–2004 and for 2005–2015 in winter are shown in Figures 4a and 4b, respectively. The mean difference is negative in most parts of northern China (north of 40°N) during 1970–2004 (Figure 4a), but it becomes positive during 2005–2015 (Figure 4b), particularly in northern Xinjiang, northern Inner Mongolia, and most parts of Northeast China.

To identify the relative contributions of GST and SAT to their difference, the averaged GST and SAT for 2005–2015 and 1970–2004 in winter are shown in Figures 4c and 4d, respectively. Compared with 1970–2004, there are evident increases of GST across most parts of China during 2005–2015, especially in northern Xinjiang, northern Inner Mongolia, and most parts of Northeast China (Figure 4c). Conversely, the averaged SATs show slight decreasing trends in some regions of China from 1970–2004 to 2005–2015, with negative values in most parts of northern China (north of 40°N, Figure 4d). The remarkable increase of GST and the slight decrease of SAT in northern China result in the increase of the GST-SAT difference in winter from 1970–2004 to 2005–2015.

To illustrate this result further, Figure 5 shows the temporal evolutions of GST and SAT and the averaged GST-SAT difference in northern China (north of 40°N) in winter for 1970–2015. From Figure 5a, it can be seen

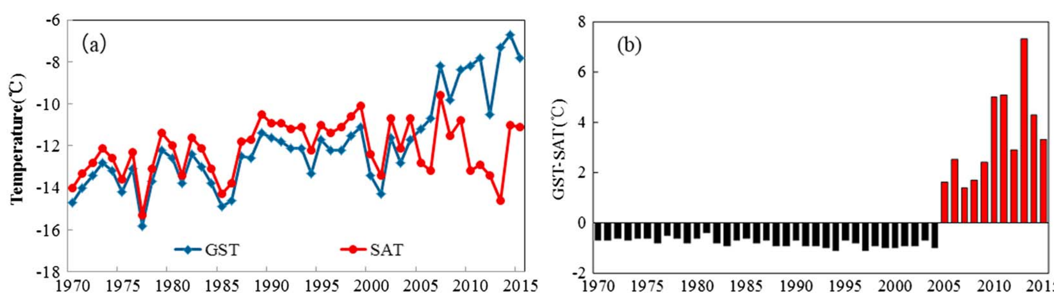

Figure 5. (a) Variations of GST and SAT and (b) difference of GST-SAT in northern China in winter over 1970–2015.

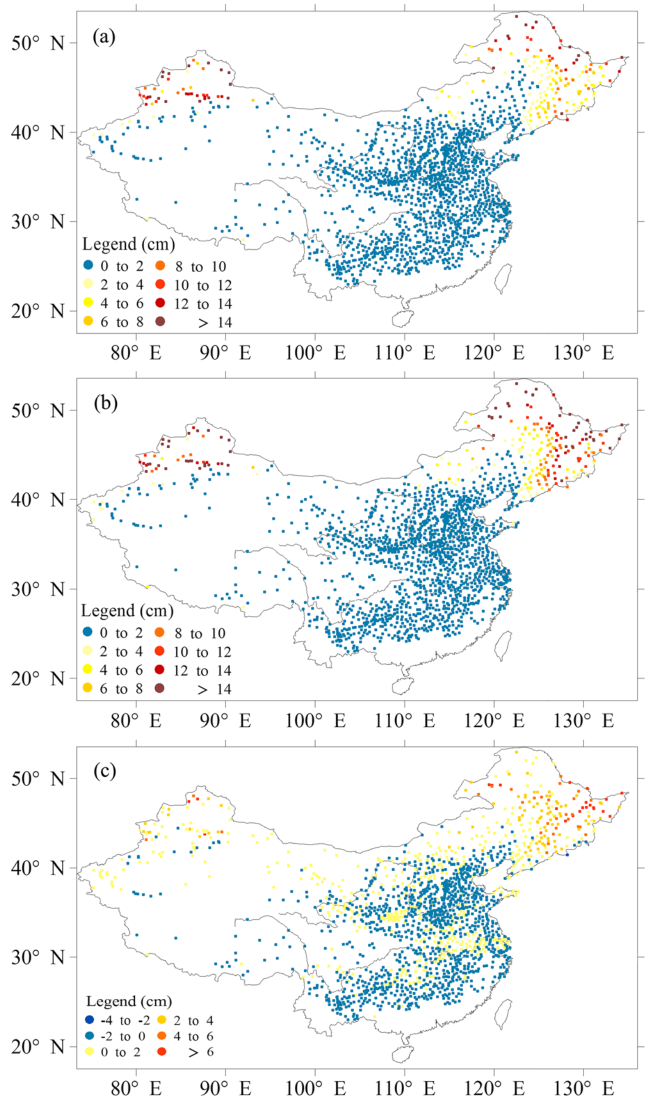

Figure 6. Spatial distributions of winter snow depth in China: (a) mean over 1970–2004, (b) mean over 2005–2015, and (c) difference between 2005–2015 and 1970–2004.

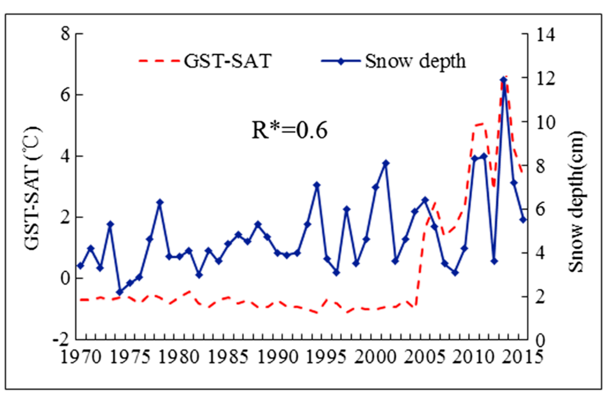

Figure 7. Variations of differences of GST-SAT and snow depth averaged in northern China (north of 40°N) in winter over 1970–2015.

that the warming tendency persists for GST after about 2000, while a slight cooling tendency is present for SAT. Consequently, there is a dramatic shift from negative to positive in the GST-SAT difference at around 2004–2005 (Figure 5b), which is consistent with the results shown in Figure 4.

3.3. Causes for the Sharp Change in GST-SAT Difference

It is necessary to explore the possible reasons for the interdecadal shift of the GST-SAT difference in winter at around 2004–2005. Among various factors, we speculate that snow variation could be important because the most significant change of the difference occurs in high latitudes in winter, e.g., the region and season having heavy snowfall (Figures 4 and 5). Moreover, recent studies have shown that snow cover can affect the difference between GST and SAT in the cold season because of the thermal insulation of snow cover [*Zhang et al*., 2005; *Bartlett et al*., 2004, 2005; *Qian et al*., 2011]. Figures 6a and 6b show the annual mean station snow depth in China in winter during 1970–2004 and 2005–2015, respectively. It can be seen that snow accumulations are thickest in most parts of northern China (north of 40°N), especially in northern Xinjiang, northern Inner Mongolia, and most parts of Northeast China, and they decrease southward during 1970–2004 and 2005–2015. The annual mean station snow depths in winter during 2005–2015 are evidently deeper than that during 1970–2004 in most of northern Xinjiang, northern Inner Mongolia, and Northeast China.

Figure 6c displays the differences of snow depth between 2005–2015 and 1970–2004 in winter. The differences are large in most parts of northern China (north of 40°N), especially in parts of northern Xinjiang, northern Inner Mongolia, and most parts of Northeast China, indicating an increase of snow depth in these regions during 2005–2015. Interestingly, the distribution pattern of snow depth difference

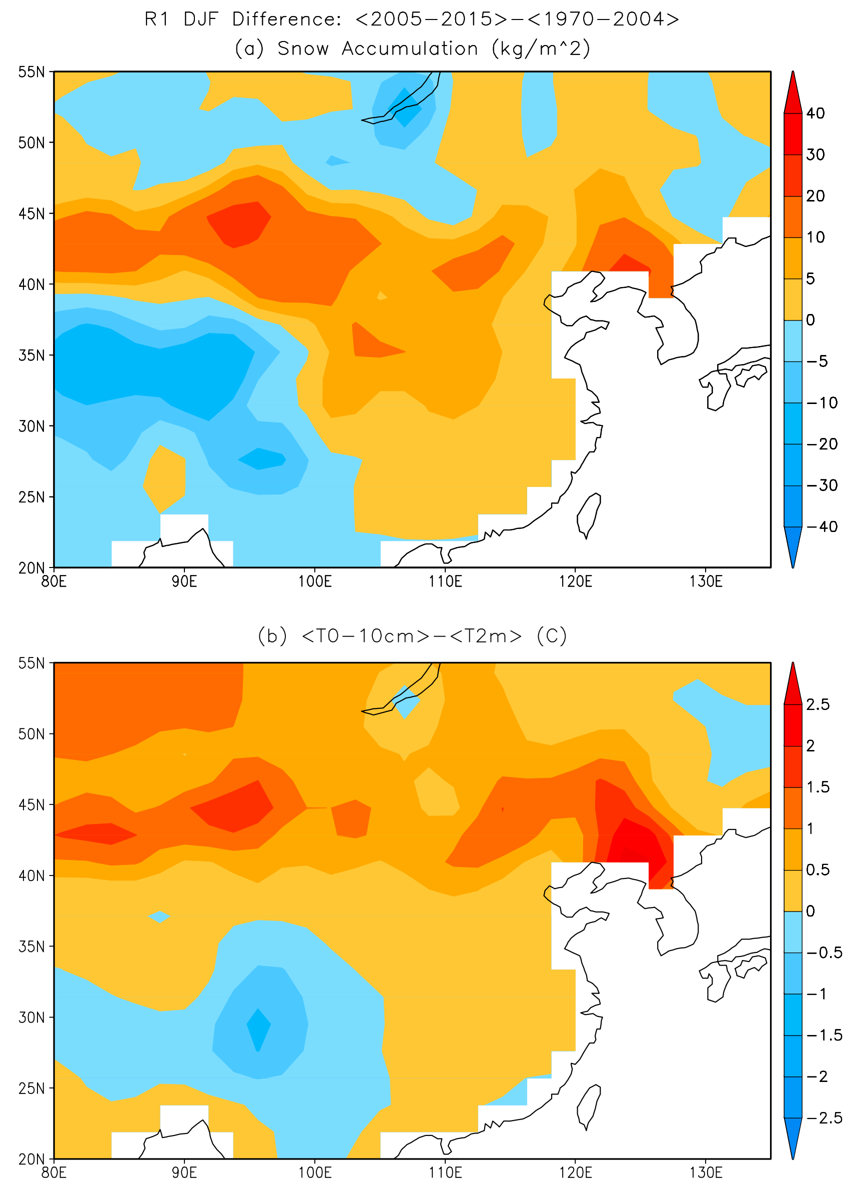

Figure 8. Difference of (a) water equivalent of surface accumulated snow depth (kg/m^2) and (b) soil temperature at 0–10 cm minus air temperature at 2 m (°C) between 1970–2004 and 2005–2015 in NCEP/NCAR reanalysis data.

(Figure 6b) is similar to that of the GST-SAT difference between 2005–2015 and 1970–2004 (Figure 4c), suggesting that increased snow depth might be an important factor in the dramatic change in the GST-SAT difference. Deep snow depth has an insulating effect that not only restricts heat loss from the ground (increasing GST) but also buffers the thermal interactions between GST and SAT [*Bartlett et al.*, 2004; *Zhang et al.*, 2005; *Qian et al.*, 2011]; meanwhile, deep snow depth is also associated with cold SATs [*Kukla*, 1978]. Thus, this is consistent with observed increase of GST and decrease of SAT in winter since 2004–2005 (Figure 4). Therefore, affected by the increase of snow depth in winter from 1970–2004 to 2005–2015, the increase of GST and decrease of SAT resulted in the increase of the GST-SAT difference in most of northern China in winter, especially in parts of northern Xinjiang, northern Inner Mongolia, and Northeast China.

Figure 7 shows the temporal variations of winter mean snow depth and winter mean GST-SAT difference averaged over northern China (north of 40°N) during 1970–2015. It can be noted that the coherence of the variations between the two time series has interdecadal variation. Their variations after 2005 are more coherent than before 2005. We speculate that the relationship between GST-SAT difference and snow depth might be nonlinear. For example, if land is covered only by a little snow, the impact on GST will be small, whereas deep snow cover has greater effect on GST but is also associated with colder SATs; consequently, the change in GST-SAT difference is positive. With further increase of snow depth after a certain threshold, its impact on GST might be expected to increase nonlinearly. Thus, snow depth increase might be one of important factors causing the interdecadal increase of the GST-SAT difference around 2004–2005.

To verify the connection between snow depths with the variations of GST-SAT difference obtained from the station data in this subsection, the NCEP/NCAR reanalysis (R1) data for 1970–2015 were examined. Monthly mean SATs and GSTs are represented by monthly mean of T2m and T0-10cm temperature in the reanalysis, respectively. Consistent with the station data (Figure 4), the reanalysis data also present a positive change of GST-SAT difference from 1970–2004 to 2005–2015 (Figure 8b). Meanwhile, snow depth, represented by water equivalent of accumulated snow depth in the reanalysis, also shows increase (Figure 8a). Such interdecadal variations of GST-SAT difference and snow depth in the reanalysis data confirm the observed relationship of the interdecadal variation of GST-SAT (Figures 4 and 5) and snow depth (Figure 6). Therefore, an increase of snow depth in northern China in winter is connected with an increase of GST-SAT difference.

3.4. Discussion

In this paper, we investigate the temporal evolution and spatial pattern of the differences between GST and SAT and the possible impact of winter snow depth on the interdecadal variation of the difference between GST and SAT. It should be noted that the relationship between snow depth and GST-SAT difference might be complex and nonlinear. Both GST and SAT can affect snow melting and accumulation. Furthermore, snow depth is just one possible influencing factor among others, e.g., atmospheric circulation, vegetation, soil moisture, and land albedo, which could affect GST, SAT, and the GST-SAT difference. Within the context of global warming, both GST and SAT would be expected to increase. However, local changes in land surface features, such as snow cover, might interrupt the trends of increase of both GST and SAT as well as their difference. Such an interruption might complicate the land-atmosphere interactions further, affecting regional-scale climate variation.

In addition, the NCEP/NCAR reanalysis data are used to verify the connection between snow cover and GST-SAT noted in the station data. We should point out that snow accumulation from the reanalysis data is generated by the model without constraint by observations. Therefore, it might have significant bias. Nevertheless, importantly, the reanalysis data reproduce the observed connection between the variations of snow depth and GST-SAT difference.

4. Conclusions

Based on monthly station data of GST and SAT, the temporal evolution and spatial distribution of the GST-SAT difference in China were analyzed. On average, GST is higher than SAT, with the largest difference in summer (3.9°C) and the smallest difference in winter (0.6°C). The spatial distribution of the GST-SAT difference also varies with season. Both GST and SAT averaged across China show significant increasing trends, with the trend of increase of GST greater than SAT both annually and seasonally, especially in winter. There is coherent temporal variation for both linear trends and interannual variabilities of GST and SAT.

Interestingly, a dramatic increase of the GST-SAT difference in winter occurred at around 2004–2005, which was caused mainly by a remarkable increase of GST and a slight decrease of SAT in northern China. Such contrasting changes of GST and SAT in winter appear at least partially, attributable to the increase of snow depth in most parts of northern China (north of 40°N) in winter, especially in northern Xinjiang and Northeast China. An increase of snow depth insulates against heat loss from the ground and increasing GST. However, increased snow depth buffers the response of SAT to GST and it cools SAT. Thus, the increase of snow depth in high latitudes of China could have caused the sharp increase in the GST-SAT difference at around 2004–2005. The connections of local snow accumulation with the variations of GST-SAT obtained from the station data were confirmed using NCEP/NCAR reanalysis data.

Acknowledgments
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